DBP CONTROL STRATEGIES FOR CONSECUTIVE SYSTEMS AND OTHER PROBLEM AREAS IN DISTRIBUTION SYSTEMS

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Abstract

Drinking water utilities in the U.S. will have to begin meeting the Stage 2 Disinfectants and Disinfection Byproducts Rule (DBPR) maximum contaminant levels (MCLs) for total trihalomethanes (TTHM) and the sum of five haloacetic acid species (HAA5) beginning in April 2012. As has been well-publicized, the Stage 2 DBPR does not change the MCLs for TTHM or HAA5, but does change the manner in which compliance is determined. Compliance will be based on locational running annual averages (LRAA) at compliance monitoring locations intended to represent areas with high TTHM and HAA5 concentrations.

The majority of previous discussions of Stage 2 DBPR compliance alternatives have focused on "in-plant" solutions. That is, strategies to be implemented at a water treatment plant to reduce distribution system disinfection byproduct (DBP) concentrations. These strategies predominantly include enhanced DBP precursor removal technologies, such as granular activated carbon or nanofiltration, or alternative disinfectants, such as chloramines. While effective, in-plant solutions may not be necessary in every case.

Distribution system optimization and treatment of the impacted area may be sufficient and more cost-effective than many of the in-plant solutions which have previously been the focus of discussions regarding Stage 2 DBPR compliance. For example, if one small area of the system poses potential compliance challenges, it can be much more economical to focus on that area of the system, rather than implement a system-wide impact. Focusing on a specific area of the system also helps to minimize the potential for unintended consequences associated with system-wide solutions, such as, corrosion control impacts, nitrification, and taste and odor.

In addition, in-plant solutions may not always be possible. Consecutive systems rely on their wholesale provider to provide them water of substantial quality to meet drinking water regulations. For most parameters, that is relatively straightforward. However, DBP concentrations can continue to increase throughout the consecutive distribution system. In such a case, it may not only be more practical or economical to focus on solutions for the consecutive system rather than in-plant solutions, but it might be the only option available.

This paper focuses on "distribution system strategies" – effective, economical, and practical solutions – to comply with the Stage 2 DBPR. It will include recent Water Research Foundation (WRF) research and case studies from throughout the U.S. of innovative strategies being used by drinking water utilities to comply with the Stage 2 DBPR. The topic is extremely timely for those systems that will struggle to comply with the new rule or who have yet to fully grasp the potential impacts of the rule to their system.

Keywords

Disinfection byproducts, DBP, distribution systems, consecutive systems, flushing, storage tank management, distribution system optimization, water age management.

Introduction

Following the discovery of chloroform in drinking water in the early 1970s, disinfection byproducts (DBPs) were first regulated in the U.S. in 1979 when the U.S. Environmental Protection Agency (USEPA) promulgated the Total Trihalomethane (TTHM) Rule. The rule established a maximum contaminant level (MCL) for TTHM of 100 ug/L. Compliance was determined based on a system-wide running annual average (RAA) of TTHM concentrations measured primarily at average residence time locations in the water distribution system.

In 1998, USEPA promulgated the Stage 1 Disinfectants and Disinfection Byproducts Rule (DBPR). The Stage 1 DBPR established maximum residual disinfectant levels (MRDLs) and maximum residual disinfectant level goals (MRDLGs) for chlorine (4 mg/L), chloramines (4 mg/L), and chlorine dioxide (0.8 mg/L). The Stage 1 DBPR also established MCLs for bromate (10 ug/L), chlorite (1.0 mg/L), TTHM (80 ug/L) and the sum of five haloacetic acid species (HAA5, 60 ug/L). Bromate and chlorite compliance determination was based on concentrations measured at the entry point to the distribution system. TTHM and HAA5 compliance was again based on system-wide RAA concentrations measured primarily at average residence time locations in the water distribution system.

The concentrations of TTHM and HAA5, unlike the majority of drinking water contaminants, continue to increase in the distribution system. As a result, customers living nearer to a water treatment plant typically receive water with lower DBP concentrations than those living at more distant locations in the distribution system. The Stage 2 DBPR was promulgated in 2006 and attempts to achieve more equitable water quality in the distribution system by changing the manner in which compliance with the TTHM and HAA5 MCLs is determined. The MCLs for TTHM and HAA5 (as well as the other regulated DBPs) remained the same under the Stage 2 DBPR; however, compliance with the TTHM and HAA5 MCLs is based on a locational running annual average (LRAA). Under this monitoring scheme, every compliance monitoring location must meet the 80 ug/L and 60 ug/L MCLs for TTHM and HAA5, respectively. Further, compliance monitoring under the Stage 2 DBPR will be conducted at locations known to have high TTHM and HAA5 concentrations rather than simply focusing on locations with average residence times. The high TTHM and HAA5 monitoring locations were selected by public water systems (PWS) during the course of an Initial Distribution System Evaluation (IDSE) conducted between 2008 and 2010 depending on system size.

Special Considerations for Consecutive Systems

As previously mentioned, DBPs are not like most drinking water contaminants in that their concentrations will continue to increase with water age in the distribution system. This poses a unique challenge for consecutive drinking water systems that purchase all or most of their water. Wholesale purchase agreements typically include volume and pressure requirements. Where water quality is included in the agreement, it generally stipulates that water quality at the entry point (master meter) to the consecutive system must meet all applicable State and federal drinking water regulations. The problem with DBPs is that although they may be within regulatory limits at the entry point, that may not be the case in higher water age areas of the consecutive system.

Many purchase agreements prohibit consecutive systems from treating or modifying the water in any way. In fact, previous DBP regulations acknowledged that consecutive systems generally have little control over water quality. For example, in some States consecutive systems were not considered out of compliance with the Stage 1 DBPR if they were unable to meet the TTHM and HAA5 MCLs. The result was significant discrepancies in how compliance was determined from State to State. Under the Stage 2 DBPR, consecutive systems must meet the same requirements as wholesale systems, including the MCLs, reporting, recordkeeping, and other requirements, such as Operational Evaluations.

The Stage 2 DBPR accepts that public water systems can periodically experience high DBP concentrations that, if repeated, would cause an MCL exceedance, but due to seasonal variations in DBP levels do not. In these cases, an Operational Evaluation is required to determine the cause of the high DBP levels. For example, a surface water system collects quarterly samples. The three most recent TTHM concentrations at one location were 50, 60, and 110 ug/L. If the next sample collected were also 110 ug/L, then this location would exceed the TTHM MCL ((50+60+110+110)__4 = 82.5). In this case, an Operational Evaluation would be required to determine the cause of the high DBP levels. For consecutive systems, this could be an annually recurring requirement due to their lack of control of water quality entering their system. It is worth noting, however, that as long as the system remains in compliance with the MCLs, no further action is required beyond the Operational Evaluation (i.e., steps to eliminate the cause of the high DBP levels are not required).

Factors Influencing DBP Formation

Identifying effective DBP control strategies requires an understanding of the factors that influence DBP formation. For consecutive systems and problem areas of the distribution system this is even more true because those systems have little or no control over some of the factors that influence DBP formation.

Water Quality

Perhaps the most significant factor influencing DBP formation is water quality. Treated waters with high DBP precursor concentrations are most likely to have high DBP concentrations in the distribution system. The type of precursor present in the finished water also influences DBP formation. For example, waters with high bromide concentrations are more likely to have issues with bromated, particularly if ozone is used in the treatment process. Similarly, some treatment processes may contribute precursors or produce DBPs. For example, some ion exchange resins have been demonstrated to contribute to n-nitrosodimethlyamine (NDMA) formation, and those systems that utilize chlorine dioxide must be aware that about 70 percent of the chlorine dioxide is converted to chlorite which has an MCL of 1 mg/L.

Temperature and pH are also a significant factor in DBP formation. DBP concentrations generally increase as water temperatures increase. DBP speciation is impacted by pH. For example, the relative concentration of TTHM to HAA5 increases with pH. In some instances, simply reducing distribution pH can be sufficient to reduce DBP levels enough to achieve compliance. Note, however, that reducing the pH to lower TTHM concentrations, may also result in an increase in HAA5 concentrations. The use of alternative sources during high temperature months (when DBP concentrations are typically higher) is one method of limiting DBP precursor concentrations in treated water. Other strategies generally include enhanced precursor removal by some form of treatment. Optimization of existing treatment, such as enhanced coagulation/softening, may be sufficient in some cases. In others, additional treatment, such as ion exchange, carbon adsorption, or nanofiltration, may be necessary.

Consecutive systems generally have little or no control over water quality factors that influence DBP formation. As such, the control strategies to address water quality issues generally have little applicability to consecutive systems and would need to be implemented by the wholesale system. However, should the wholesale system choose to implement such a strategy, the consecutive system would also see improvements in DBP levels.

Disinfectant Type and Residual

The disinfectant(s) used in the treatment process and the dose at which they are applied also has a significant on DBP formation. First and foremost, some DBPs are only formed by certain disinfectants. For example, bromate is a byproduct of ozonation, and chlorite is usually only a concern when chlorine dioxide is used (although it can be found as an impurity in sodium hypochlorite or a byproduct of sodium hypochlorite degradation). Ozone and chlorine dioxide can also have a beneficial impact on TTHM and HAA5 formation in that they will oxidize their precursors, resulting in lower TTHM and HAA5 concentrations. With respect to TTHM and HAA5, they are primarily byproducts of chlorination and, to a lesser extent, chloramination.

Reducing the chlorine dose to the minimum that is needed to achieve primary disinfection and maintain an acceptable minimum residual in the distribution system can be very effective for the control of DBP levels in the distribution system. Oxidation of precursors using ozone or chlorine dioxide and optimization of primary disinfection are not typically applicable to consecutive systems and would need to be implemented by the wholesaler. Further optimization of chlorination practices, such as booster disinfection, may be applicable to consecutive systems depending on limitations of the purchase agreement.

Water Age

As has been stated several times previously, water age significantly impacts DBP formation in water distribution systems. DBP concentrations generally increase with water age. Water age is also the one factor influencing DBP formation over which consecutive systems have the most control. While it is true that consecutive systems have no control over the age of the water entering their system, after it enters the consecutive systems generally have the latitude to adjust operations to minimize water age without subjection to limitations in the purchase agreement.

When possible, it is desirable for wholesale systems to receive water from a transmission main rather than the distribution network of a wholesale system or upstream consecutive system. After water enters the consecutive distribution system, the consecutive system should optimize system configuration and operation to reduce water age. This not only provides benefits to the consecutive system making the improvements, but also to any subsequent/downstream consecutive system.

Strategies to minimize water age include storage tank management, elimination of dead-ends (physical or hydraulic), flushing, and “right-sizing” distribution infrastructure. Consecutive systems generally have complete control over all of these options, as such they can be extremely effective for the control of DBPs in consecutive systems.

DBP Control Strategies

While this paper discusses DBP control strategies for consecutive systems, the reality of the situation is that the water age in many wholesale distribution systems may be as high or higher than that of a consecutive system. Thus, while the term “consecutive systems” is used throughout this discussion, the strategies presented are equally applicable to areas within the wholesale distribution system that may also have high DBP concentrations. In fact, in the case of problem areas within a wholesale system it may be easier to implement an effective DBP control strategy as there are likely to be fewer restrictions on modifications to the system and the wholesale system may have more experienced operations staff.

The majority of previous discussions of Stage 2 DBPR compliance alternatives have focused on “in-plant” solutions. That is, strategies to be implemented at a water treatment plant to reduce distribution system DBP concentrations. These strategies predominantly include enhanced DBP precursor removal technologies, such as granular activated carbon or nanofiltration, or alternative disinfectants, such as chloramines. While effective, in-plant solutions may not be necessary in every case. Distribution system optimization and treatment of the impacted area may be sufficient and more cost-effective than many of the in-plant solutions which have previously been the focus of discussions regarding Stage 2 DBPR compliance.

Storage Tank Operations

Poorly mixed and poorly operated storage tanks can have significant impacts on distribution system DBP concentrations. **Table 1** presents temperature, free chlorine, TTHM, and HAA5 concentrations in the top and bottom of three tanks. The data demonstrate how water quality and DBP levels are impacted by storage facility operations.

Table 1. Impact of Storage Tank Operations on DBP Concentrations

Tank Type (Volume, Mgal)	Temperature (º F)		Free Chlorine Residual (mg/L)		TTHM (µg/L)		HAA5 (µg/L)	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Elevated (1.0)	79	78	1.0	1.7	100	76	82	61
Elevated (0.5)	81	77	0.1	0.8	120	110	86	75
Standpipe (4.0)	81	80	0.0	1.0	98	99	31	61

Tank 1 Significant variation in free chlorine concentrations at the top and bottom of the tank are indicative of poor tank mixing. As a result, DBP levels in the top of the tank are approximately 33 percent higher than in the bottom of the tank. This can result in slugs of poorer water quality entering the system and jeopardize Stage 2 DBPR compliance.

Tank 2 DBP levels in both the top and bottom of this tank are high and pose potential problems.

Thermal stratification and significant variations in free chlorine are indicative of poor mixing. However, in this case, because there is very little chlorine left in the top of the tank DBP formation has nearly stopped.

Tank 3 Again, significant variation in free chlorine concentrations at the top and bottom of the tank are indicative of poor tank mixing. However, because there is no chlorine residual remaining in the top of the tank, DBP formation has stopped, and in fact biodegradation of HAA5 has begun as evidenced by the lower HAA5 concentration in the top of the tank.

Increasing volume turnover and improved tank mixing are the two most effective strategies for minimizing water age in storage tanks and reducing DBP concentrations. Volume turnover in storage tanks is generally expressed in one of two ways: the percent of volume that is exchanged in one day or the average time that the entire volume of water is discharged from the storage facility. Kirmeyer, et al. (1999) recommended a minimum turnover of 3 to 5 days (20 to 33 percent turnover per day). **Figure 1** shows an example of tank levels in a well-operated tank over a 24-hour period. Note that when the tank is draining, it drains to a set low tank level before filling and then fills until it hits a high tank level. This is optimum from a turnover and mixing perspective.

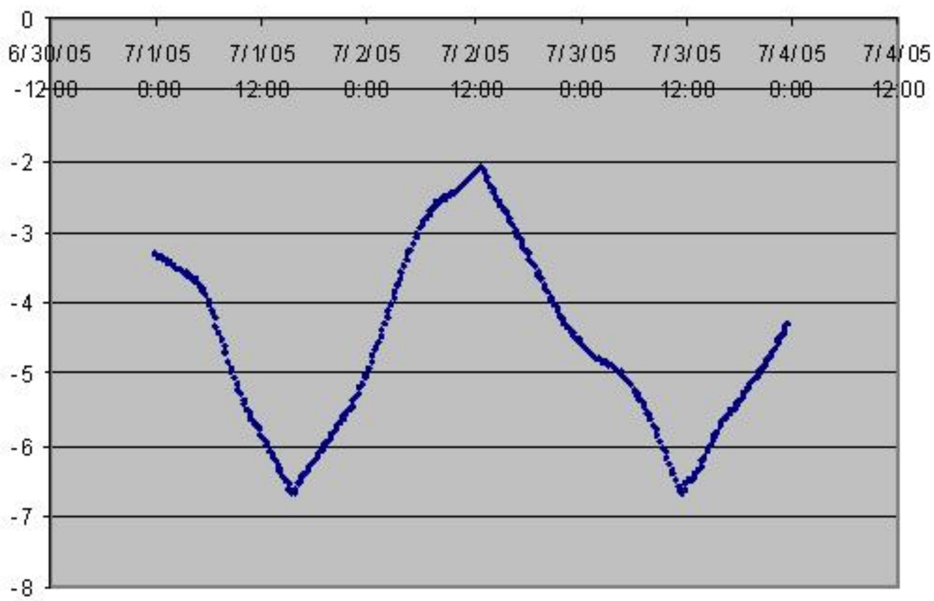

Figure 1. Example of a Well-Operated Tank

Inlet momentum (velocity × flow rate) is a key factor for mixing of water in storage tanks. The higher the inlet momentum, the better the mixing characteristic in the storage tanks. Increasing the flow rate is one way to increase inlet momentum, but may not be practical due to limitations of system hydraulics. For example, a pump may not be available at the tank location and the distribution system pressure may not be high enough to get desirable increases in flow rates. In some cases, even if a pump were available, it may not be possible to increase the pumping rate into the tanks. In such cases, it may be more feasible to increase the inlet momentum by increasing the velocity with a reduced inlet diameter.

To encourage good mixing, the inlet should directed away from any obstacles, such as a tank wall, the bottom of the tank, or deflectors (Grayman, et al., 2000). The location and orientation of the inlet pipe relative to the tank walls can have a significant impact on mixing characteristics. For example, when the height of a tank is much larger than the diameter or width, the location of the inlet pipe at the bottom of the tank in the horizontal direction is likely to cause the water jet to hit the vertical wall of the tank resulting in loss of inlet momentum and incomplete water mixing.

Figure 2 shows the impact of inlet orientation on tank mixing and shows improvements implement to improve tank mixing and water quality. The tank depicted is a 2 million gallon elevated storage tank. The tank had a single 24-inch inlet/outlet located to one side of an access manway. The inlet momentum was insufficient to completely mix the upper levels of the tank and the manway was a barrier to mixing in half of the tank. A modified inlet/outlet consisting of four 8-inch nozzles directed to the upper quadrants of the tank and a 6-inch nozzle directed vertically was able to achieve complete tank mixing without modifications to any of the other operating conditions.

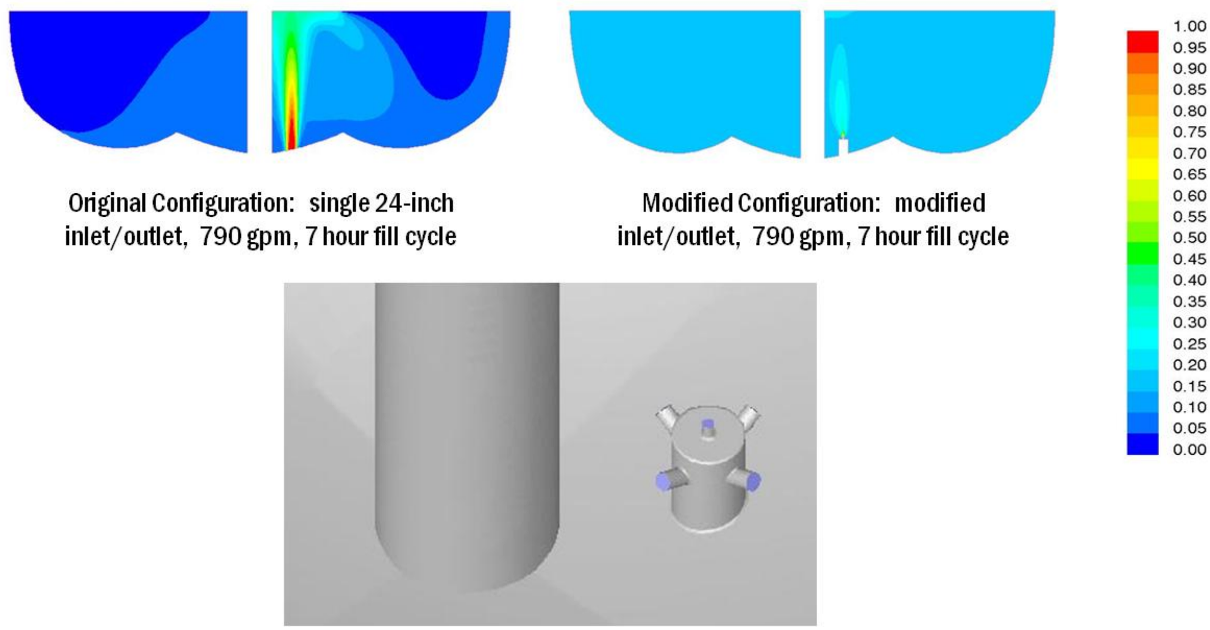

Figure 2. Impact of Inlet Configuration on Tank Mixing.

Baffles are used to encourage plug flow and to eliminate short-circuiting and dead zones in contact tanks. Plug flow in distribution system storage facilities results in increases in water age, higher DBP levels, and loss of disinfectant residual. Consequently, baffles should be avoided in distribution system storage facilities to reduce water age, lower DBP concentrations, and generally improve water quality.

Water Age Management

As discussed above, improving tank turnover and mixing can significantly reduce water age in the distribution system. However, the design and operation of the distribution system can also significantly impact water age. Dead ends, areas with low flow, oversized distribution mains and excessive storage increase water age and can result in increases in DBP levels. Looping to eliminate dead-ends and increase flow in low flow areas can reduce water age and reduce DBP levels; however, care must be taken to ensure adequate demand exists to induce flow in the low flow area. Otherwise, looping may just create a larger dead-end zone.

Most water systems are designed based on fire flow rather than water quality requirements. That results in a lot of oversized water mains with low flow and high water age under normal operating conditions. In other cases, reduction in demand (e.g., loss of a large industrial user) or designs based on future demands that have yet to come can also result in excessive water age. The problem often compounds itself as water moves through the system resulting in very high water age and DBP levels at the ends of the system. The installation of smaller mains or parallel mains (which also improves system redundancy) is one method to help control water age. Inducing higher system demands by adding new industrial users, flushing, or blowoffs can also be an effective strategy for controlling water age and reducing DBP levels. For example, the City of St. Petersburg, Florida recently converted several public parks from reclaimed water to potable water for irrigation to address water age-related water quality issues in the ends of their distribution system.

Figure 3 shows the effect of automatic flushing on distribution system DBP levels in one Midwest utility. In this case, the local water utility acquired a small consecutive system that was connected to the main system by an approximately four mile long, 16-inch transmission main. The consecutive system had approximately 400 residents and an average day demand of about 40,000 gallons. Water age increased in the transmission main by approximately 5 days, resulting in low chlorine residuals and high DBP levels in the distribution system. The utility chose to implement automatic flushing at two locations in the consecutive system. As a result of the flushing, water age decreased in the consecutive system from 7 to 10 days to 4 to 7 days and DBP concentrations were reduced by 30 to 40 percent.

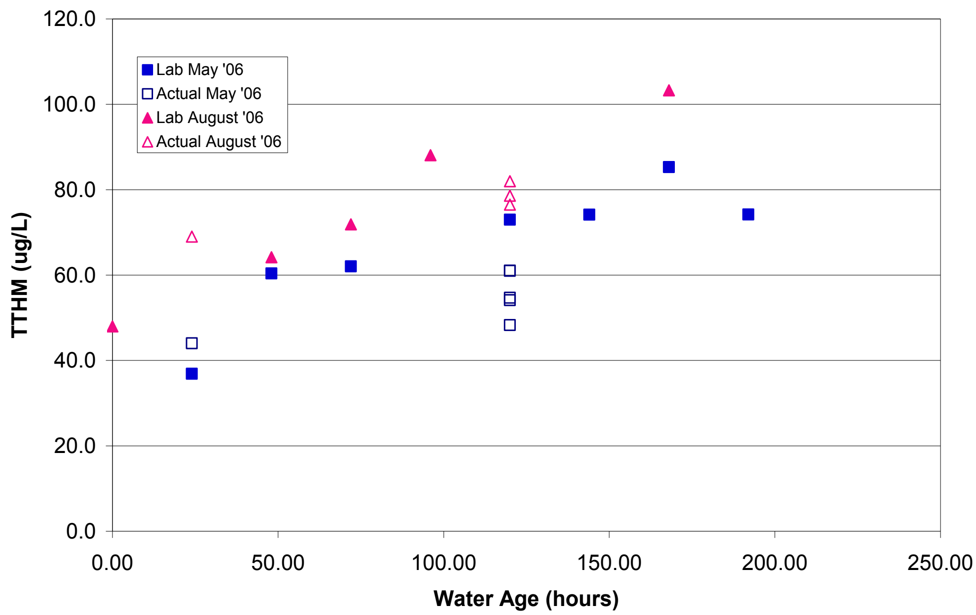

Figure 3. Effect of Flushing on Consecutive System TTHM Concentrations

Disinfection Optimization

DBP formation is controlled by a first-order rate reaction and is directly proportional to the applied disinfectant dose and precursor concentration. Excess application of chlorine, or poorly controlled chlorine addition, can lead to significant increases in distribution system DBP levels. Though typically beyond the control of the consecutive system, disinfection optimization can have extremely beneficial impacts to DBP levels in consecutive systems and other areas with high water age. **Figure 4** shows hourly flow rates and chlorine residual from a surface water treatment plant. Note that the chlorine residual is consistently approximately 2 mg/L. Flow, however, varies from 15 to 65 MGD. During those periods of low flow, the contact time in the plant clearwell is approximately 4 times greater than at 65 MGD. In plants with considerable clearwell storage, this can lead to significant DBP formation at the treatment plant before the treated water ever enters the distribution system. A chlorine dosing strategy designed around meeting primary disinfection requirements, then boosting the residual as necessary prior to entering the distribution system can have significant impacts on distribution system DBP levels.

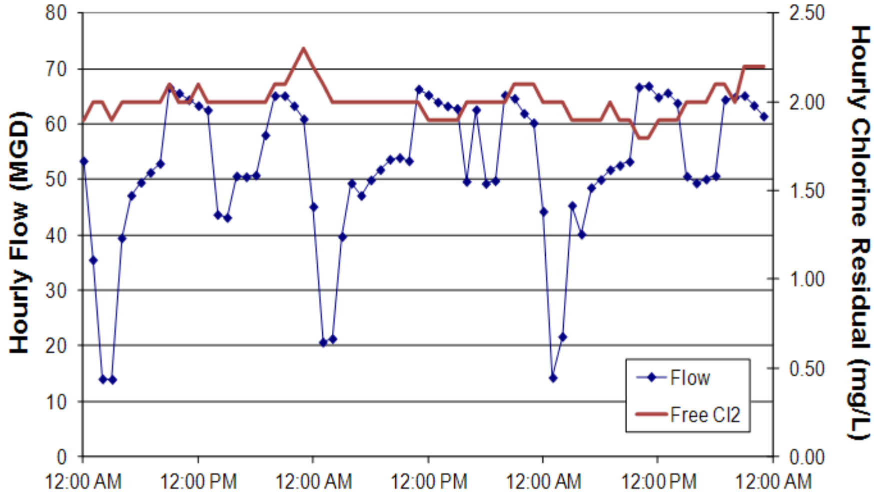

Figure 4. Comparison of Peak Hourly Flow Rates and Chlorine Residual Levels

In addition to optimization of chlorination practices at the treatment plant, alternative disinfection strategies, such as booster chlorination, chloramination, and use of chlorine dioxide for oxidation of DBP precursors can also be effective for the control of DBPs in consecutive systems and other problem areas of the distribution system. **Table 2** provides a summary of the impact of several alternative disinfection strategies on distribution system DBP levels.

Table 2. Comparison of Alternative Disinfection Strategies (Chowdhury, et al., 2009)

Alternative disinfection strategy		Percent Reduction*	
		TTHM	HAA5
Chloramine (1 hour) Target 3 mg/L chloramine residual, ammonia addition after 1 hour of free Cl^2 contact time	1 hour	14	14
	1 day	55	48
	8 days	74	68
Chloramine (1 day) 25% of initial chlorine dose, chlorine boost and ammonia addition after 1 day to achieve target 3 mg/L chloramine residual	1 hour	21	13
	1 day	19	8
	8 days	56	43
Chlorine dioxide Chlorine dioxide target of 0.4 mg/L after 4 hours for primary disinfection, free chlorine for secondary with target of 0.5 – 1 mg/L after 8 days	1 hour	50	45
	1 day	46	49
	8 days	40	40
Booster Chlorination Target 1 mg/L residual @ 1 day, then boost to achieve 0.5-1 mg/L after 8 days	1 hour	21	18
	1 day	22	31
	8 days	0	8

** Bench-scale test results. Compared to conventional chlorination (i.e., one-time addition of chlorine for primary and secondary disinfection. Average results from 5 utilities.*

Chloramination by the wholesale system was the most effective means for controlling DBPs in consecutive systems. However, for a variety of reasons, many systems would prefer to continue to utilize free chlorine rather than convert to chloramines. Chloramination by the consecutive system (wholesaler remains on free chlorine) was also effective, but has many of the same implementation issues as chloramination at the treatment plant. Use of chlorine dioxide for primary disinfection, which oxidizes DBP precursors, was also very effective.

Booster chlorination is frequently touted as an effective means of reducing distribution system DBP levels. Note in **Table 2** that while booster chlorination was effective for reducing DBP concentrations within the distribution system, it had minimal impact where chlorination was followed by long detention times. This indicates that to be effective multiple booster stations may be required in systems with high water age.

Localized Treatment

Localized treatment of areas with high DBP concentrations can be very effective, particularly when water age management strategies or disinfection optimization are insufficient or non-viable. The most common method of localized treatment is aeration/air stripping of TTHM in distribution system storage tanks. Aeration can be extremely effective, particularly where the predominant THM specie present is chloroform. Aeration is not effective for the control of HAA5. There are a number of aeration systems available. **Figure 5** presents the results of one study which demonstrated approximately 35 to 55 percent removal of TTHM by aeration.

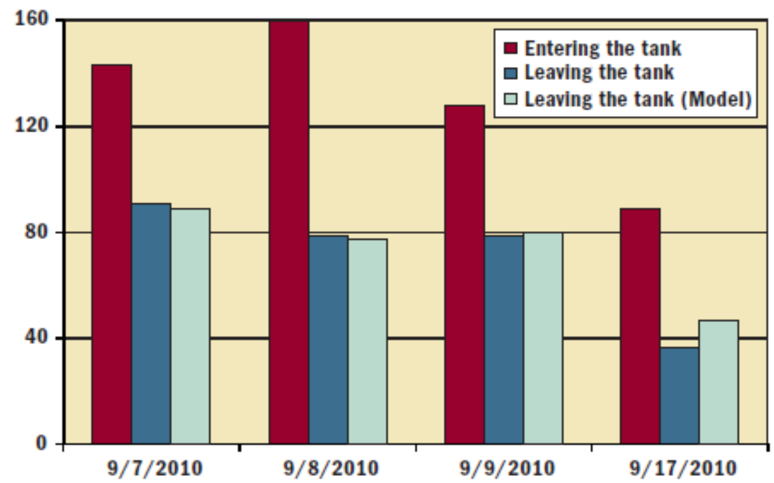

Figure 5. Comparison of TTHM Levels Before and After Aeration in a Distribution Storage Tank (Fiske, et al., 2010)

As mentioned, aeration can be effective for the control of TTHM, but not HAA5. Where HAA5 is a concern or the aeration/air stripping may not be practical or feasible (e.g., less volatile species of TTHM dominate), other treatment options exist. Activated carbon can be utilized and is effective for the control of both TTHM and HAA5. American Water has recently investigated the use of membrane treatment in the distribution system for control of volatile organic compounds. Results indicate the treatment to be effective for the control of VOCs and indicate it is likely to be effective for the control of TTHM (Raczko, 2012).

Conclusions and Recommendations

The majority of previous discussions of Stage 2 DBPR compliance alternatives have focused on “in-plant” solutions. While effective, in-plant solutions may not be necessary in every case. Distribution system optimization and treatment of the impacted area may be sufficient and more cost-effective than many of the in-plant solutions which have previously been the focus of discussions regarding Stage 2 DBPR compliance. For example, if one small area of the system poses potential compliance challenges, it can be much more economical to focus on that area of the system, rather than implement a system-wide impact. Focusing on a specific area of the system also helps to minimize the potential for unintended consequences associated with system-wide solutions, such as, corrosion control impacts, nitrification, and taste and odor.

In addition, in-plant solutions may not always be possible. Consecutive systems rely on their wholesale provider to provide them water of substantial quality to meet drinking water regulations. For most parameters, that is relatively straightforward. However, DBP concentrations can continue to increase throughout the consecutive distribution system. In such a case, it may not only be more practical or economical to focus on solutions for the consecutive system rather than in-plant solutions, but it might be the only option available.

Consecutive System Recommendations

Though there are steps that can be taken by consecutive systems to minimize DBP formation, they are ultimately dependent upon the wholesaler to provide water that enables them to comply with the Stage 2 DBPR. Consecutive systems should work with their wholesale provider to develop an understanding of distribution system operations on DBP formation. Bench studies can be used to establish target consecutive system entry point DBP levels and develop an understanding of how consecutive system operations impact DBP levels. From there, consecutive systems can develop and implement strategies to reduce water age or remove DBPs in problem areas of their system. If consecutive system DBP control strategies are insufficient to achieve compliance with the Stage 2 DBPR, then the consecutive system will need to work with the wholesaler to develop a strategy.

Wholesale System Recommendations

Wholesale systems are encouraged to work collaboratively with consecutive systems to develop strategies to reduce distribution system DBP levels. Though purchase agreements may not stipulate compliance with DBP regulations at the ends of the system, if the consecutive system has made a good faith effort to reduce water age and control DBPs, then wholesalers should take additional steps to help reduce DBP levels. It is worth noting that if a consecutive system has DBP issues, then the wholesaler may also have DBP issues in the ends of their system as water age in the two systems is frequently similar.

Wholesale systems may be able to implement low-cost strategies, such as treatment optimization, optimization of disinfection practices, or strategies to reduce water age in their system which may prove sufficient to reduce DBP levels in consecutive systems. When optimization strategies are insufficient, alternative disinfection strategies, such as the use of chlorine dioxide, may be more cost effective than enhanced precursor removal options, such as activated carbon or nanofiltration.

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